

Title of the Invention

MESOPOROUS SILICA, MESOPOROUS SILICA COMPOSITE MATERIAL, AND
PROCESSES FOR PRODUCTION THEREOF

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Background of the Invention and Related Art Statement

[0001] The present invention relates to a mesoporous
silica, a mesoporous silica composite material, and processes
for producing such a silica and such a composite material.

10 More particularly, the present invention relates to a
mesoporous silica and a mesoporous silica composite material,
both superior in alkali resistance and suitably used
particularly as a separation membrane (e.g. a ceramic
membrane) or a catalytic support for solid-liquid system, in
15 which an alkaline liquid may be used; as well as to processes
for producing such a silica and such a composite material.

[0002] In recent years, attention has been paid to
mesoporous silica with uniform mesopore structure, typified
by MCM-41 (see JP-A-5-503499) and FSM-16 (see J. Am. Chem.
20 Soc., 114, 10834, 1992). Mesoporous silica is synthesized
using the micelle structure of a surfactant as a template;
therefore, mesoporous silica has a structure in which pores
with nano meter size in diameter are arranged periodically,
and the size of the pore diameter is dependent upon the
25 carbon chain length of the surfactant. Accordingly,
mesoporous silica is characterized in that it has pores with
uniform diameter and the diameter can be controlled
appropriately. Owing to this characteristics, mesoporous
silica is expected to be used as a separation membrane
30 enabling a high selectivity and a catalytic support with high

performance; and processes for synthesis of mesoporous silica have been proposed in, for example, Chem. Commun., 2147, 1998 and J. Memb. Sci., 182, 235, 2001.

[0003] In some fields using a separation membrane enabling a high selectivity and a catalytic support of high performance, for example, a medicinal field and a food field, alkaline reagents are used. With conventional such separation membranes and catalytic support, however, there have been cases that their washing with such an alkaline reagent is impossible or they have no sufficient durability to the alkaline reagent. Therefore, conventional separation membranes and catalytic support have not been fully satisfactory in general applicability. No sufficient solution has been proposed yet to such a problem.

Summary of the Invention

[0004] The present invention aims at providing a mesoporous silica and a mesoporous silica composite material, both superior in alkali resistance and suitably used particularly as a separation membrane (e.g. a ceramic membrane) or a catalytic support for solid-liquid system, in which an alkaline liquid may be used; as well as processes for producing such a silica and such a composite material.

[0005] In order to achieve the above aim, the present invention provides the following mesoporous silica, mesoporous silica composite material and processes for producing such silica and such a composite material.

[0006]

[1] A mesoporous silica having uniform mesopores and a periodic structure, which contains a Zr element in the form

of a Si-O-Zr bond and wherein the Zr content in the Si-O-Zr bond, represented by $[Zr/(Si + Zr)]$ is 0.05 to 20 mole %.

[0007]

[2] A mesoporous silica according to the above [1], which

5 has a particulate form or a filmy form.

[0008]

[3] A mesoporous silica according to the above [1] or [2], wherein the diameters of the mesopores are 1.0 to 3.0 nm and the volume of the mesopores is 0.5 to 1.0 cc/g.

10 [0009]

[4] A mesoporous silica according to any of the above [1] to [3], which has an alkali resistance index of larger than 10 in terms of pH when an alkali resistance test is conducted and evaluation is made based on the peak intensity appearing

15 at $2\theta = 2.5^\circ$ of X-ray diffraction.

[0010]

[5] A mesoporous silica composite material comprising a porous substrate and a mesoporous silica according to any of the above [1] to [4], deposited thereon.

20 [0011]

[6] A process for producing a mesoporous silica, which comprises mixing a solution containing a surfactant, with a solution or dispersion containing a Si source and a Zr source, stirring the resulting mixture to form a gel, placing the gel

25 in a pressure vessel and keeping the gel at a predetermined temperature, then calcining the gel to form particles, and molding the particles into a desired shape.

[0012]

[7] A process for producing a mesoporous silica composite

30 material, which comprises dipping a porous substrate in a

solution or dispersion containing a Si source and a Zr source, adding the porous substrate and the solution or dispersion containing a Si source and a Zr source, into a solution containing a surfactant, stirring the resulting mixture to form a gel, placing the gel and the porous substrate in a pressure vessel and keeping them at a predetermined temperature, then calcignig them.

Brief Description of the Drawing

[0013] Figs. 1(a), 1(b), 1(c) and 1(d) are graphs each showing the X-ray diffraction pattern of a mesoporous silica before and after an alkali resistance test.

Detailed Description of the Invention

[0014] Specific description is made below on embodiments of the mesoporous silica, mesoporous silica composite material and processes for producing such a silica and such a composite material, all according to the present invention.

[0015] The mesoporous silica of the present invention has uniform mesopores and a periodic structure of Si-O bond, wherein the Si-O bond contains a Zr element in the form of a Si-O-Zr bond and the Zr content in the Si-O-Zr bond, represented by $[Zr/(Si + Zr)]$ is 0.05 to 20 mole %, preferably 3 to 5 mole %.

[0016] When the Zr content in the Si-O-Zr bond is less than 0.05 mole %, the alkali resistance of the mesoporous silica is insufficient. When the Zr content is more than 20 mole %, the degree of the periodic structure of the mesoporous silica is low.

[0017] The Zr content in the Si-O-Zr bond can be measured

by dissolving the mesoporous silica in hydrofluoric acid and analyzing the resulting solution using ICP.

[0018] The mesoporous silica of the present invention can take a particulate form or a filmy form.

5 [0019] Or, the mesoporous silica may be deposited on a porous substrate to use as a mesoporous silica composite material.

[0020] In one process for producing a particulate porous silica, a solution containing a surfactant is mixed and
10 stirred with a solution or dispersion containing a Si source and a Zr source, to form a gel; the gel is placed in a pressure vessel and kept at a predetermined temperature; then, particles are calcined; and the particles are molded into a desired shape.

15 [0021] In one specific process for producing a particulate mesoporous silica, a solution containing a surfactant and a pH-adjusting agent is mixed and stirred with a solution containing a Si source and a Zr source, to form a gel; the gel is placed in a pressure vessel and kept at a
20 predetermined temperature; after a predetermined time, the gel is taken out and calcined to remove the surfactant present in the pores formed.

[0022] In one process for producing a filmy mesoporous silica (a composite material of a porous substrate and a
25 filmy mesoporous silica), a porous substrate is dipped in a solution or dispersion containing a Si source and a Zr source; the porous substrate and the solution or dispersion containing a Si source and a Zr source are added into a solution containing a surfactant; the resulting mixture is
30 stirred to form a gel; the gel and the porous substrate are

placed in a pressure vessel and kept at a predetermined temperature; and calcining is conducted.

[0023] In one specific process for producing a filmy mesoporous silica (a composite material of a porous substrate and a filmy mesoporous silica), a porous substrate is beforehand dipped in a solution or dispersion containing a Si source and a Zr source; the porous substrate and the solution or dispersion are added into a solution containing a surfactant and a pH-adjusting agent; the resulting mixture is stirred to form a gel; the gel and the porous substrate are placed in a pressure vessel, kept at a predetermined temperature and taken out; then, calcination is conducted to obtain a mesoporous silica composite material wherein a mesoporous silica film is deposited on a porous substrate.

In this process, it is important in order to obtain a filmy mesoporous silica that the porous substrate is beforehand dipped in the solution or dispersion containing a Si source and a Zr source. When the porous substrate is not dipped beforehand in the solution or dispersion containing a Si source and a Zr source, only particles of mesoporous silica are formed and no mesoporous silica film is formed on the porous substrate.

[0024] As the porous substrate used in the present invention, there can be mentioned, for example, alumina, cordierite, zirconia, titania and stainless steel.

By the above process, a thin film consisting of a mesoporous silica having pore diameters of 1.0 to 2.6 nm can be formed on a porous substrate. This thin film is not peeled off when touched by hand. Incidentally, a particulate mesoporous silica and a filmy mesoporous silica are the same

in substance although different in form; therefore, both of them have alkali resistance.

[0025] As the surfactant used in the present invention, there can be mentioned, for example, cetyltrimethylammonium bromide (CTAB), cetyltrimethylphosphonium, octadecyltrimethylphosphonium, benzyltrimethylammonium, cetylpyridinium, myristyltrimethylammonium, decyltrimethylammonium, dodecyltrimethylammonium and dimethyldidodecylammonium and the like.

[0026] As the Si source used in the present invention, there can be mentioned, for example, colloidal silica, sodium silicate, silicon alkoxides, tetramethylammonium silicate and tetraethylorthosilicate (TEOS) and the like.

[0027] As the Zr source used in the present invention, there can be mentioned, for example, zirconium-containing compounds such as zirconium alkoxide and the like.

[0028] As the pH-adjusting agent used as necessary in the present invention, there can be mentioned, for example, acids such as sulfuric acid, hydrochloric acid and the like; and alkalis such as sodium hydroxide, ammonia and the like.

Incidentally, the pH of the reaction system in the mesoporous silica production process is preferably adjusted to 1 to 3 when an acid is used, and to 10 to 13 when an alkali is used.

[0029] With respect to the proportions of the individual components used in producing the mesoporous silica or composite material thereof, of the present invention, the proportion of the pH-adjusting agent (sodium hydroxide) to the Si source, in terms of molar ratio of sodium hydroxide/Si source, is preferably 0.2 to 0.7, more preferably 0.4 to 0.6; and the proportion of the surfactant to the Si source, in

terms of molar ratio of surfactant/Si source, is preferably 0.03 to 0.8, more preferably 0.04 to 0.6.

[0030] Specifically, when the mesoporous silica produced is MCM-41, the molar ratio of sodium hydroxide/Si source is preferably 0.4 to 0.6, and the molar ratio of surfactant/Si source is preferably 0.04 to 0.1. When the mesoporous silica produced is MCM-48, the molar ratio of sodium hydroxide/Si source is preferably 0.4 to 0.6, and the molar ratio of surfactant/Si source is preferably 0.4 to 0.6.

[0031] In producing the mesoporous silica or the composite material thereof, of the present invention, the temperature employed in forming a gel is preferably room temperature to 30°C. When this temperature is too high, the raw materials for the gel may not reach the inside of the pores of the porous substrate.

[0032] The formed gel is kept preferably at 20 to 180°C and, when 90°C is employed, the keeping time is preferably 48 hours.

[0033] The conditions employed in calcining the gel or the gel and the porous substrate are preferably 300 to 500°C (temperature) and 5 hours (keeping time) when 500°C is employed.

[0034] The present invention is described more specifically below by way of Examples. However, the present invention is in no way restricted by these Examples.

[0035]

Examples 1 to 6 (Production of zirconia-containing MCM-41)

In a beaker were placed 50 g of deionized water, 0.364 g of cetyltrimethylammonium bromide (CTAB) as a surfactant and 2.5 g of NaOH (4 mol/l), followed by stirring at 30°C for

30 minutes to obtain a solution 1. To this solution 1 was added a mixed solution of tetraethylorthosilicate (TEOS) (a Si source) and tetrapropylzirconium (TPOZ) or tetrabutylzirconium (TBOZ) (a Zr source). The resulting mixture was stirred at 30°C for 2 hours to form a gel. The gel was placed in a pressure vessel and allowed to stand at 90°C for 72 hours. The resulting product was taken out of the pressure vessel and calcined at 500°C for 4 hours to remove the surfactant (CTAB). XRD diffraction confirmed that the product was MCM-41. The product was measured for mesopore diameter and mesopore volume and also subjected to an alkali resistance test.

[0036] In Table 1 are shown the proportions of TEOS and TPOZ or TBOZ, the Zr content in zirconia-containing MCM-41, i.e. $Zr/(Si + Zr)$ determined by ICP analysis, the mesopore diameter and mesopore volume of zirconia-containing MCM-41, and the result of alkali resistance test of zirconia-containing MCM-41.

[0037]

Examples 7 to 12 (Production of zirconia-containing MCM-48)

In a beaker were placed 44 g of deionized water, 5.83 g of CTAB and 5.0 g of NaOH (4 mol/l), followed by stirring at 30°C for 30 minutes to obtain a solution 2. To this solution 2 was added a mixed solution of TEOS and tetrapropylzirconium (TPOZ) or tetrabutylzirconium (TBOZ). The resulting mixture was stirred at 30°C for 2 hours to form a gel. The gel was placed in a pressure vessel and allowed to stand for 72 hours. The resulting product was taken out of the pressure vessel and fired at 500°C for 4 hours to remove the surfactant (CTAB). XRD diffraction confirmed that the product was MCM-

48. The product was measured for mesopore diameter and mesopore volume and also subjected to an alkali resistance test.

[0038] In Table 1 are shown the proportions of TEOS and TPOZ or TBOZ, the Zr content in zirconia-containing MCM-48, i.e. $\text{Zr}/(\text{Si} + \text{Zr})$ determined by ICP analysis, the mesopore diameter and mesopore volume of zirconia-containing MCM-48, and the result of alkali resistance test of zirconia-containing MCM-48.

[0039]

Comparative Example 1 (Production of MCM-41)

In a beaker were placed 50 g of deionized water, 0.364 g of CTAB and 2.5 g of NaOH (4 mol/l), followed by stirring at 30°C, to obtain a solution 3. 30 minutes later, 4.17 g of TEOS was added to the solution 3, and the resulting mixture was stirred at 30°C for 2 hours to form a gel. The gel was placed in a pressure vessel and allowed to stand at 90°C for 72 hours. The resulting material was taken out of the pressure vessel and calcined at 500°C for 4 hours to remove the surfactant (CTAB). XRD diffraction confirmed that the product was MCM-41. The product was measured for mesopore diameter and mesopore volume and also subjected to an alkali resistance test.

[0040] In Table 2 are shown the proportions of the individual components used, the mesopore diameter and mesopore volume of MCM-41, and the result of alkali resistance test of MCM-41.

[0041]

Comparative Example 2 (Production of MCM-48)

In a beaker were placed 44 g of deionized water, 5.83 g

of CTAB and 5 g of NaOH (4 mol/l), followed by stirring at 30°C, to obtain a solution 4. 30 minutes later, 8.33 g of TEOS was added to the solution 4, and the resulting mixture was stirred for 2 hours to form a gel. The gel was placed in a pressure vessel and allowed to stand at 90°C for 72 hours. The resulting material was taken out of the pressure vessel and calcined at 500°C for 4 hours to remove the surfactant (CTAB). XRD diffraction confirmed that the product was MCM-48. The product was measured for mesopore diameter and mesopore volume and also subjected to an alkali resistance test.

[0042] In Table 2 are shown the proportions of the individual components used, the mesopore diameter and mesopore volume of MCM-48, and the result of alkali resistance test of MCM-48.

Table 1

	Examples											
	1	2	3	4	5	6	7	8	9	10	11	12
Si source	TEOS 4.04	TEOS 3.96	TEOS 3.75	TEOS 4.04	TEOS 3.96	TEOS 3.75	TEOS 7.92	TEOS 7.5	TEOS 7.08	TEOS 7.92	TEOS 7.5	TEOS 7.08
Zr source	TPOZ 0.26	TPOZ 0.44	TPOZ 0.89	TBOZ 0.27	TBOZ 0.45	TBOZ 0.90	TPOZ 0.53	TPOZ 0.89	TPOZ 1.78	TBOZ 0.54	TBOZ 0.90	RBOZ 1.81
Zr/(Si+Zr)	0.03	0.05	0.10	0.03	0.05	0.10	0.03	0.05	0.10	0.03	0.05	0.10
Surfactant	CTAB	CTAB	CTAB	CTAB	CTAB	CTAB	CTAB	CTAB	CTAB	CTAB	CTAB	CTAB
PH-adjusting agent	0.364 NaOH	0.364 NaOH	0.364 NaOH	0.364 NaOH	0.364 NaOH	0.364 NaOH	5.83 NaOH	5.83 NaOH	5.83 NaOH	5.83 NaOH	5.83 NaOH	5.83 NaOH
Product	Zr-MCM- 41	Zr-MCM- 41	Zr-MCM- 41	Zr-MCM- 41	Zr-MCM- 41	Zr-MCM- 41	Zr-MCM- 48	Zr-MCM- 48	Zr-MCM- 48	Zr-MCM- 48	Zr-MCM- 48	Zr-MCM- 48
Mesopore diameter	2.6						2.8					
Mesopore volume	0.9						1.0					
Alkali resistance	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5	pH 11.5

Table 2

	Comparative Examples	
	1	2
Si source	TEOS	TEOS
	4.17	4.17
Surfactant	CTAB	CTAB
	0.364	5.83
pH-adjusting agent	NaOH	NaOH
	2.5	5.0
Product	MCM-41	MCM-48
Mesopore diameter	2.7	2.4
Mesopore volume	0.8	0.9
Alkali resistance	Broken at pH 10	Broken at pH 10

[0043] The measurements of the mesopore diameter and mesopore volume of each product, the XRD diffraction for identification of each product, and the alkali resistance test for each product were conducted as follows.

Mesopore diameter: Calculated from the adsorption isotherm of N₂ at 77 K according to the BJH method.

Mesopore volume: Calculated from the amount of adsorbed N₂ at 77 K.

XRD diffraction: Measured in a 2θ range of 15.8 to 8°, using CuK_α.

Alkali resistance test: There were prepared solutions of pH 10 to 11.5 each comprising NaHCO₃ and NaOH. 0.1 g of a sample was placed in 10 ml of each solution, followed by stirring at 30°C for 3 hours and drying. The resulting material was subjected to XRD diffraction to confirm whether or not the structure of the sample was maintained.

[0044] In Figs. 1(a), 1(b), 1(c) and 1(d) are shown the X-ray diffraction patterns of mesoporous silicas before and after alkali resistance test. In Figs. 1(a), 1(b), 1(c) and

1(d), the axis of ordinate refers to a peak intensity and the axis of abscissa refers to 2θ . Figs. 1(a), 1(b), 1(c) and 1(d) are the X-ray diffraction patterns before and after alkali resistance test, obtained in Comparative Example 1,

5 Example 1, Comparative Example 2 and Example 2, respectively. In Comparative Examples 1 and 2, the structure of mesoporous silica was broken at pH 10; in contrast, in Examples 1 and 2, the structure of mesoporous silica was maintained even at pH 11.5.

10 [0045] As described above, the present invention can provide a mesoporous silica and a mesoporous silica composite material, both superior in alkali resistance and suitably used particularly as a separation membrane (e.g. a ceramic membrane) or a catalytic support for solid-liquid system, in
15 which an alkaline liquid may be used; as well as processes for producing such a silica and such a composite material.